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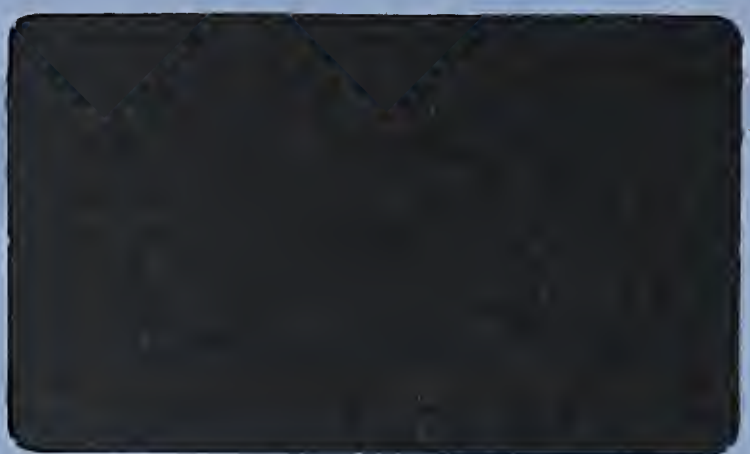
INVENTORY OF GROUND-WATER RESOURCES

TECHNICAL PAPER



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UPPER MISSOURI RIVER BASIN

MONTANA

LEVEL B STUDY

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INVENTORY OF GROUND-WATER RESOURCES

TECHNICAL PAPER

MISSOURI RIVER BASIN COMMISSION

February, 1980

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GLOSSARY OF TERMS

aquifer.--A formation, group of formations, or part of a formation that contains sufficient saturated permeable material to yield significant quantities of water to wells and springs. An aquifer is sometimes referred to as a ground-water reservoir.

aquifer test.--A field procedure used to determine the transmissive and storage characteristics of an aquifer. Commonly consists of measurement of the hydraulic or chemical response of the aquifer to a pumped well, injection well, changes in stream stage, or tracers.

analog model.--Constructed device used to simulate the response of a water-resource system to natural or man-induced conditions. Often an electrical circuit with properties analogous to the hydraulic properties of the water system.

artificial recharge.--Recharge of an aquifer through a man-made structure such as a pit or injection well.

base flow.--Natural discharge from the ground-water reservoir to a stream. The discharge maintains streamflow in the absence of surface runoff.

confined aquifer.--An aquifer containing ground water that is confined under pressure between relatively impermeable or significantly less permeable material, and that will rise above the top of the aquifer.

evapotranspiration.--Loss of water by evaporation from wet surfaces and by transpiration through plants.

gain-and-loss study.--A series of surface-water flow measurements in a selected reach of a stream to determine gains or losses in streamflow attributable to interchanges between the stream and associated aquifer.

gaining stream.--A stream or reach of a stream whose flow is being increased by inflow of ground water.

ground-water discharge.--Loss of water from a ground-water reservoir.

ground-water divide.--A zone in an aquifer from which ground water flows in different directions.

ground-water mining.--The process, deliberate or inadvertent, of extracting ground water from a source at a rate so in excess of the replenishment that the ground-water level declines persistently, threatening actual exhaustion of the supply or at least a decline of pumping levels to uneconomical depths.

ground-water recharge.--Addition of water to a ground-water reservoir.

hydraulic conductivity.--The rate at which water may be transmitted through a unit area of an aquifer, under standardized conditions.

lake evaporation.--Evaporation from a large lake or surface reservoir.

losing stream.--A stream or reach of a stream that is losing water to the ground.

mathematical model.--Mathematical technique used to simulate the response of a water-resource system to natural or man-induced conditions. Normally consists of machine-readable data and flow equations that are solved, and results printed by a high speed computer.

phreatophyte.--A plant that depends for its water supply upon ground water that lies within reach of its roots. Commonly found along streams or where the water table is close to the land surface.

potentiometric surface.--An imaginary surface connecting points to which water would rise in tightly cased wells from a given point in an aquifer. A map of the potentiometric surface is useful to indicate direction of ground-water movement.

return flow.--That part of irrigation water that is not consumed by evapotranspiration and that returns to its source or another body of water. The term is also applied to the water that is discharged from industrial plants. Also called return water.

salvage.--Capture of water supplies by reducing evapotranspiration or other discharge from the ground-water reservoir, or by inducing increase in recharge to the ground-water reservoir.

specific yield.--The volume of water that can be drained by gravity from a saturated rock or soil in relation to the volume of the rock or soil.

storage coefficient.--The volume of water released from storage or taken into storage in an aquifer, per unit surface area of the aquifer per unit change in head.

stream-aquifer system.--A stream and adjacent aquifer that are hydraulically connected. An interchange of water between the stream and aquifer may occur.

stream depletion.--Reduction of streamflow in a stream-aquifer system due to withdrawals from wells that capture streamflow or intercept ground water that would have discharged to the stream.

transmissivity.--The rate at which ground water may be transmitted through a cross section of unit width over the entire thickness of an aquifer, under standardized conditions.

unconfined aquifer.--An aquifer that has a water table and contains ground water that is not confined under pressure by overlying impermeable or significantly less permeable material.

underflow.--Downstream movement of ground water in a valley-fill aquifer.

water management.--Design and implementation of plans to utilize, or at least consider, the best combination of available water supplies to meet water-resource objectives, with due regard to water quality.

water table.--The imaginary surface within an unconfined aquifer at which the pressure is atmospheric.

INTRODUCTION

Purpose and scope

Ground-water resources in the Upper Missouri River Basin constitute a large part of the total water resources. In parts of the basin, ground-water resources are barely used; in other parts of the basin the use of ground water contributes greatly to overall water supply. Full utilization of ground water in water management certainly has not been reached. The purpose of this report is to encourage further consideration of the use of ground water in regional water planning and management by:

(1) Describing the general occurrence, characteristics, and behavior of ground-water resources in the study area.

(2) Indicating general areas in which hydrologic data and interpretive investigations of ground water are needed.

(3) Suggesting preliminary ways to broaden water management to include fuller use of ground water.

(4) Explaining proven methods for investigating and utilizing ground-water supplies.

Work group membership

This work item was addressed by a three-member work group. The Geological Survey of the U.S. Department of Interior was the lead agency. As the lead agency, it was their responsibility to coordinate the input of other members They were also responsible for helping determine the elements contained in the plan of study and the methods to be used. The agencies and the individuals designated to represent each agency are shown below:

U.S. Geological Survey (USGS) -- Rickard D. Hutchinson

Montana Bureau of Mines and Geology (BMG)-Robert Bergantino

Montana Department of Natural Resources and Conservation (DNRC) - Tom Patton

The work group commenced its efforts with an organizational meeting in June 1978. That meeting was used to evaluate what needed to be done and to assign responsibilities. Subsequent meetings were used to determine progress and find solutions to problems.

The USGS compiled hydrogeologic maps east of longitude 110° W., compiled records of observation wells for the study area, and prepared the final report. The BMG provided mapping in the area west of longitude 110° W. and made computer searches of high-capacity wells in the study area. DNRC provided consultation during the first two months of the work period until Mr. Patton was permanently reassigned to BMG.

Demands for water--past, present, and future

Recent trends in water use in the United States have been summarized by Murray (1968) and Murray and Reeves (1972 and 1977). Ground- and surface-water use in the entire Missouri River Basin Region increased 20 percent from 1965 to 1970 and 50 percent from 1970 to 1975, as shown in table 1. Total ground-water use in the region increased by more than 67 percent from 1965 to 1970 and 69 percent from 1970 to 1975. Ground-water use also increased for each use category except industrial.

Irrigation use was increased by more acreage brought under cultivation and efforts to increase crop yield by applying more water. Irrigation use from ground-water sources increased by 67 percent between 1965 and 1970 and increased 96 percent from 1970 and 1975. These rates greatly exceed the rates of increase from surface-water sources during the same periods. The use of sprinklers for irrigation purposes is a major cause of the increased acreage and increased use of ground water for irrigation. Water withdrawn for irrigation probably will continue to increase throughout the region because under present economic conditions, irrigated-land farming is more profitable than dry-land farming. About 75 percent of the irrigated acreage is for pasture land. Irrigation of small-grain crops is about 10 percent of the total acreage.

Table 1 --Water use, in million gallons per day, for entire Missouri River Basin, 1965, 1970, and 1975

[Figures do not add to totals because of independent rounding.]

Use	Water withdrawn, 1965			Water withdrawn, 1970			Water withdrawn, 1975		
	Ground water	Surface water	Ground and surface water	Ground water	Surface water	Ground and surface water	Ground water	Surface water	Ground and surface water
Irrigation	2,700	13,000	16,000	4,500	14,000	19,000	8,800	20,000	29,000
Industrial	340	2,400	2,700	860	3,200	4,100	740	4,000	4,700
Public supply	340	630	970	430	590	1,000	490	720	1,200
Rural	300	170	470	380	180	560	430	190	620
Total	3,700	16,000	20,000	6,200	18,000	24,000	10,500	25,000	35,000

Industrial use of ground water in the region increased by 153 percent from 1965 to 1970 but decreased by 14 percent from 1970 and 1975. The decline was due to an estimated 160 million gallons per day reduction in the use of saline ground water. Fresh ground water industrial use increased about 6 percent from 1970 to 1975. Water requirements for energy development are likely to cause a further increase in the use of ground water by industry. Surface-minable coal deposits occur in several areas of eastern Montana. The coal may occur within aquifers, and in some areas the coal itself is an aquifer. In other areas the coal is part of the confining beds that may overlie or underlie other aquifers. Coal mining, coal transportation, and coal utilization affect ground water in various ways. Mining may disrupt natural recharge, movement, storage, and discharge of ground water. Water quality changes are common due to leaching associated with changes in the flow system. The Surface Mining Control and Reclamation Act, Public Law 95-87, was passed in 1977, partly to insure that future mining practices preserve ground-and surface-water resources, and to restore previously mined areas to more natural hydrologic conditions.

Expected high demand for coal in the future will affect ground-water supplies and quality. The effect will have to be closely analyzed prior to development and monitored during the mining and post-mining phases. The use of ground water for steam generating plants near coal fields may also be common. Water from the plants is either consumed or returned to the aquifer or streams at high temperatures, causing thermal pollution.

Ground water is pumped in Montana by the petroleum industry for waterflooding, a process in which water is used to flush petroleum out of reservoir rocks. Production wells are usually completed in bedrock aquifers that are deeply buried and frequently contain saline water.

Increases in public supply and rural use of ground water are also shown in table 1. The rates of increase indicate an increasing reliance on ground water.

Demand for water, including ground water, is influenced by economic factors, especially the price for water that users are willing to pay. Normally, users of water for irrigation or rural purposes require low-cost supplies; users of water for industrial or public-supply purposes can afford to pay higher prices for supplies. Competition for water supplies may cause a shift in water demand and use toward those users that are willing to pay higher prices, provided that a change in use is permitted by regulations. The market price of water also varies with current quantity available. The quantity of water available for use may be increased by effective water management. Increased quantities will lower prices if accompanied by favorable production conditions. The quantity available for use may be decreased by overdrafts or by seasonal or extended drouths. Decreased quantities will raise prices if accompanied by unfavorable production conditions such as increased withdrawal costs due to declining water levels or increased treatment costs due to impaired water quality.

Constraints to basin-wide management of water resources will be numerous and varied. Lack of ground-water information in the Upper Missouri River Basin is a constraint that limits development. Proper planning will improve the level of information and permit more utilization of ground water. Water apportionment rules should lead to efficient use of supplies through modern water-management techniques. Apportionment rules should be based on knowledge of all sources of water supply and on knowledge of the behavior of water-resource systems in order to facilitate efficient use. Costly projects such as water transfer, reservoir construction, deep drilling, or water treatment may not be necessary if all alternatives in water management are considered.

Legal and regulatory constraints by state agencies also influence ground-water management. Development of a State Water Plan for Montana was directed by the 1967 State Legislature, and efforts toward this plan have been the work of the Montana Department of Natural Resources and Conservation. The Department of Health and Environmental Sciences has the responsibility for the water quality of Montana's waters, along with public water supplies and wastewater management. The Montana Universities Joint Water Resources Research Center is the center of academic oriented water research in Montana. It carries out specialized water studies designed by academicians, sometimes at the specific requests of water resource management agencies. The Montana Bureau of Mines and Geology is located in Butte and is the agency responsible for well-log data preservation for the state.

No permit is required for appropriation of ground-water supplies for domestic, agricultural, or livestock purposes if the maximum yield of the source well is less than 100 gpm. It is only necessary to complete a form within 60 days after completion of the well. A certificate of water right is sent to the owner through the appropriate county clerk and recorder office.

The Department of Natural Resources and Conservation must give prior approval of water rights for wells yielding 100 gpm or more and for wells within controlled ground-water areas. Controlled ground-water areas may be established to protect prior water rights or to protect public health in areas subject to pollution of water supplies.

GROUND-WATER RESOURCES

Ground water of the Upper Missouri River Basin occurs in a variety of aquifers that have been classified as alluvial deposits of sand and gravel, glacial deposits, basin-fill deposits of sand and gravel; and formations of sandstone, siltstone, fractured sandy clay, limestone, and dolomite. The alluvium of Quaternary age is generally located along stream valleys. Glacial deposits of Quaternary age in the study area are mostly in a broad band along and to the north of the Missouri River. Unconsolidated basin-fill deposits of Tertiary age that are thousands of feet thick occur in intermontane valleys of southwestern Montana. Sandstone aquifers ranging in age from Cambrian to Cretaceous lie near the land surface and in basins of various depths. The Madison Limestone aquifer of Late Paleozoic age underlies most of the study area, but remains mostly untested. In addition the basin may contain undiscovered aquifers capable of yielding large water supplies.

Recharge to the aquifers is derived from precipitation, irrigation water, leaky reservoirs, losing streams, and leakage from other aquifers. Natural ground-water movement is generally in the direction of surface drainage; however, movement in deep aquifers may be unrelated to surface drainage because ground-water movement between surface drainage basins has been identified. The aquifers discharge to streams, springs, phreatophytes, wells, and to other aquifers. Major aquifers occurring at the land surface in the study area are listed in greater detail in the following section. A series of maps (figures 1-19) covering the study area, showing the approximate location of the aquifer described, are provided under separate cover.

Table 2.--Summary of major surficial aquifers in the Upper Missouri River Basin

Source of supply (map symbol)	Location	Yield to wells (gpm)	Suggestions for improved hydrologic data and analyses and water management	Outlook for future use if suggestions are followed
Valley-fill aquifers (Qal, Qg)	Along major streams and their tributaries	10-4,500	Mapping and test drilling to determine location and type of boundaries, aquifer thickness and extent. Aquifer testing to prepare maps of transmissivity and specific yield. Preparation of water-table maps. Gain-and-loss studies in streams. Water-management analysis of stream-aquifer system.	Improved water supply by controlled changes in streamflow and ground-water storage. Additional reuse of available supply. Storage benefits from artificial recharge.

Table 2.--Summary of major surficial aquifers in the Upper Missouri River Basin--continued

Source of supply (map symbol)	Location	Yield to wells (gal/min)	Suggestions for improved hydrologic data and analyses and water management	Outlook for future use if suggestions are followed
Glacial-deposit aquifers (unmapped)	Northern Montana	0-1,000	Test drilling to locate aquifers. Statistical analyses of drillers' logs, aquifer transmissivity, well yield, well dependability, and water quality to define major aquifers and saline ground-water resources. Ground water and streamflow sampling under low flow conditions. Preparation of water-table maps and depth-to-water maps. Changes in agricultural practices to reduce recharge. Withdrawal and disposal of saline water from areas where conditions permit.	Increased and more dependable water supply. Reclamation of land in northern Montana affected by saline seeps. Use of saline ground water.

Table 2.--Summary of major surficial aquifers in the Upper Missouri River Basin--continued

Source of supply (map symbol)	Location	Yield to wells (gal/min)	Suggestions for improved hydrologic data and analyses and water management	Outlook for future use if suggestions are followed
Basin-fill aquifers (QTg, QTt, and Tg)	Southwestern Montana	10-2,400	Incorporation of ground water into water-management plans that include all water supplies, current status of each, and known behavior of hydrologic system. Exploration for additional basin-fill aquifers.	Reduced shortages, even during drought of several years' duration. Possible discovery of additional ground-water supplies.
Flaxville aquifer (Tf)	North-central Montana	10-1,258	Preparation of additional water-table maps. Aquifer testing to determine transmissivity and specific yield. Gain-and-loss studies along streams hydraulically connected to the aquifer.	Improved understanding of aquifer potential. Conjunctive use of ground and surface water.

Table 2.--Summary of major surficial aquifers in the Upper Missouri River Basin--continued

Source of supply (map symbol)	Location	Yield to wells (gal/min)	Suggestions for improved hydrologic data and analyses and water management	Outlook for future use if suggestions are followed
Fox Hills lower Hell Creek aquifer (Kfh)	Eastern Montana	10-250	Statistical compilation of well logs, aquifer properties, well characteristics, and water quality. Preparation of areally extensive mathematical models. Control of flowing wells.	Increased success in drilling dependable wells yielding good quality water.
Eagle and Virgelle aquifers (Kev, Ke)	Northwestern and central Montana	5-250	Control of flowing wells and implementation of other conservation practices. Use of other supplies for industry. Artificial-recharge experiments to determine if fractures and vertical hydraulic conductivity of aquifer will facilitate rapid recharge.	Reduction of ground-water mining and pumping lift in wells.

Table 2.--Summary of major surficial aquifers in the Upper Missouri River Basin--continued

Source of supply (map symbol)	Location	Yield to wells (gal/min)	Suggestions for improved hydrologic data and analyses and water management	Outlook for future use if suggestions are followed
Judith River and Kootenai aquifers (Kjr, Kk)	Northwestern and central Montana	5-300	Preparation of potentiometric maps, aquifer testing and water-quality sampling.	Development of ground-water supply designed to take advantage of possible interaquifer leakage.

Table 2.--Summary of major surficial aquifers in the Upper Missouri River Basin--continued

Source of supply (map symbol)	Location	Yield to wells (gpm)	Suggestions for improved hydrologic data and analyses and water management	Outlook for future use if suggestions are followed
Madison and associated Paleozoic aquifers (Pz)	Mountainous areas	100 to several thousand	Preparation of improved potentiometric map and additional aquifer testing to define areal distribution of transmissivity and storage. Inventory of springs and measurement of spring discharges. Identification of aquifers hydraulically connected to Madison aquifer and measurement of observation wells completed in the aquifers. Preparation of maps showing areal distribution. Continued use of simulation models to determine optimal development plans.	Development of large supply derived principally from salvaged rejected recharge, reduced discharge, and leakage to the Madison from other aquifers. Development of saline water resources.

Valley-fill alluvial aquifers

The valley-fill alluvial aquifers consist of unconsolidated gravel, sand, silt, and clay, and are located along, and hydraulically connected to, the principal streams and their tributaries. Therefore the aquifers tend to be elongate. In general, aquifers in main stream valleys are more extensive and thicker than aquifers in tributary valleys. Valley-fill aquifers are absent in some reaches of the main streams and in the upper reaches of most tributaries. In parts of northern Montana the aquifers are not distinguishable from glacial aquifers and are inundated in some areas by surface-water reservoirs. Data describing the areal extent and saturated thickness of the valley-fill aquifers are poorly known in most parts of the region, and information is needed to design plans for improved use of the aquifers.

Valley-fill aquifers are recharged by precipitation, irrigation water, leakage from other aquifers, and losing streams. Ground-water movement normally is in the downstream direction so underflow in tributary valleys contributes to the ground water in the main valleys. In general the ground water in the valley-fill aquifers is in transit toward the lower part of the basin. Discharge from the aquifers is by drainage to streams, evapotranspiration, wells, and leakage to other aquifers. Evapotranspiration occurs where phreatophytes grow along stream valleys or anywhere the water table lies close to the land surface, as in many valleys in the study area. Large-capacity wells completed in valley-fill alluvium yield as much as 4,500 gallons per minute (gpm) along a tributary of the Smith River near White Sulphur Springs. Generally the maximum yields from wells in tributary valleys are smaller because aquifer materials are finer grained and aquifers are less extensive than those in the main stream valleys. More water-table maps and gain-and-loss studies in streams are needed to define the flow systems of the valley-fill aquifers.

Aquifer testing of valley-fill aquifers indicates that the transmissivity and specific yield are normally large. In many areas additional aquifer testing is needed in order to prepare maps showing the areal distribution of transmissivity and specific yield for use in models and planning. Aquifer testing can be conducted either by pumping large-capacity wells and observing the effect on the water table, or by measuring fluctuations of the water table that are caused by changes in the stage of the stream (Ferris, 1950).

Valley-fill alluvial aquifers and the associated streams in the study area form stream-aquifer systems in which pumping of water wells in various locations may be used to control the timing of depletion of ground water in storage and streams, the two sources that supply the wells. The value of water management for the stream-aquifer system is apparent because the timing of some of the effects on the stream and aquifer can be selected. During periods of surplus or adequate surface runoff it may be desirable to pump wells near the stream, in order to deplete surplus streamflow rapidly When surface runoff is small or when all streamflow is allocated among the other users, it may be desirable to pump wells distant from the stream and delay depletion of the stream until a later period when streamflow is more abundant. Withdrawals from wells in the valley-fill aquifers of the study area deplete the streamflow and affect downstream users. However, part of the streamflow probably is derived from ground water so the surface and ground water in the stream-aquifer system actually constitutes a single water supply

Glacial aquifers

Unconsolidated aquifers also occur in glacial deposits that extend in a belt as much as 125 miles (mi) wide across nearly all of the study area. The deposits reach a maximum thickness of about 300 feet (ft) and contain sand and gravel aquifers in the form of buried channel deposits, extensive outwash deposits, and lenticular outwash deposits. Many aquifers in the glacial deposits are not exposed at the land surface and must be located by test drilling, geologic interpretation, or geophysical exploration. Glacial aquifers are recharged by precipitation, streams, or leakage from bedrock aquifers below the glacial deposits. Ground water in the glacial aquifers is discharged to streams, springs, underlying bedrock, evapotranspiration, or wells. Well yields are extremely variable but potentially are as much as 1,000 gpm. Flowing wells derive water from aquifers confined by clay beds. Withdrawals from wells are used for domestic, livestock, municipal, and irrigation purposes.

Saline seeps from glacial aquifers in northern Montana have affected a growing area that currently is about 170,000 acres (Ac) of land; the seeps make the land too saline for most uses (Marvin Miller, Montana Bureau of Mines and Geology, oral commun., 1976). Water-quality sampling of ground water and streamflow under low-flow conditions helps to delineate reaches of the streams affected by the seeps. Water-table maps and depth-to-water maps help to delineate areas that may be subject to future damage and help to develop schemes to reduce or halt the spread of the seep areas. Reducing recharge to the glacial aquifers by planting crops that transpire more water helps to moderate the problem. In some cases it may be possible to remove the saline water by wells or drains and evaporate the water from ponds.

Several agencies in Montana have small drilling programs to define aquifers in glacial deposits, but more extensive and ordered exploration is needed. Exploration procedures for aquifers in glacial deposits have been discussed by Winter (1975). Aquifers in glacial deposits are difficult to locate because they are not mappable from the surface and cannot be correlated over large distances. Furthermore, the aquifers may have been formed during different stages of glaciation, complicating the geological interpretation of their origin and distribution. Statistical analyses of data describing drillers' logs, rock types, well yields, well dependability, and aquifer transmissivity are needed to provide information useful in locating the aquifers, and to describe areal variations in the hydraulic properties of the aquifers.

Basin-fill aquifers

Basin-fill aquifers in southwestern Montana consist mostly of poorly consolidated deposits of gravel, sand, silt, and clay of Tertiary age and attain a maximum thickness of about 6,000 ft in intermontane valleys. Basin-fill aquifers are overlain by valley-fill alluvial aquifers in many areas. Basin-fill aquifers are recharged by precipitation, irrigation water, and streams. Ground water moves in the downstream direction. Aquifers discharge to streams, to the atmosphere by evapotranspiration where the water table is close to the land surface, and to wells drilled for irrigation, domestic, livestock, and industrial purposes. Although basin-fill aquifers are not as transmissive as the overlying valley-fill alluvium, wells yield as much as 2,400 gpm.

An extensive analysis of the ground-water resources in the basin-fill aquifers of the Gallatin Valley near Bozeman, Montana was prepared by Hackett and others (1960). The authors proposed greater conjunctive use of ground water and surface water to intercept more of the water that passes downstream.

Artificial recharge is proposed as a means to store the occasional surface-water surplus in the ground-water reservoir. Similar studies should be made for each of the basin-fill aquifers.

A comprehensive water-management plan could be designed so that each year a water supply could be obtained efficiently from a combination of available sources. The combination would depend on the current available supply in each source, the known behavior of the hydrologic system, snowmelt forecasts, and runoff forecasts. The large thickness of the basin-fill deposits indicates that a large volume of ground water is available, which would be particularly useful if temporary depletion of stored supplies became necessary during a drought of several years duration

Flaxville aquifer

The Flaxville aquifer occurs in parts of north-central Montana north of the Missouri River. It is reported to be from a few feet to 100 ft thick (Collier and Thom, 1918). The aquifer consists mostly of sand and gravel but includes cobbles as much as 12 inches (in) in size. The material is almost exclusively quartzite and chert in the study area.

Aquifer recharge is largely from precipitation and irrigation. Discharge is to streams, springs, and to irrigation, municipal, stock, and domestic wells. Some wells in northeastern Blaine County yield as much as 1,258 gpm. Additional water-table maps, aquifer testing, and gain and loss studies in streams would help in the design of plans to capture more natural discharge from the aquifer.

Fox Hills-lower Hell Creek aquifer

The Fox Hills and lower Hell Creek sandstone units form an areally extensive and persistent aquifer throughout most of eastern Montana. The aquifer is probably recharged by precipitation where it is exposed at the land surface and by leakage from adjacent rocks. Natural discharge is by upward leakage through confining beds. Ground-water movement is generally towards the center of the Williston Basin in western North Dakota. Industrial, municipal, and domestic wells generally have a maximum yield of about 250 gpm.

A statistical compilation and analysis of well logs, aquifer properties, well characteristics, and water quality is needed to improve the level of understanding of ground-water occurrence in the Fox Hills and lower Hell Creek aquifer. More aquifer testing and potentiometric maps are needed in order to predict the hydrologic response to future development. Finally, an areally extensive mathematical model is needed for evaluation of the aquifer. The model could provide information on suspected leakage from overlying aquifers and aid in the design of plans for optimal use of the supply.

Eagle and Virgelle aquifers

The Virgelle Sandstone occurs in northwestern Montana. In central Montana the Virgelle is the basal member of the Eagle Formation. The Virgelle consists of sandstone and shale and attains a maximum thickness of about 180 ft. Precipitation and leakage from overlying glacial deposits recharge the Virgelle in the Cut Bank area (Zimmerman, 1967). Discharge in the Cut Bank area is to streams and springs, and to wells that yield as much as 250 gpm. Zimmerman (1967) suggested that plugging of flowing wells would help to preserve the supply in the aquifer but the wells are not located easily.

In central Montana the Eagle yields as much as 75 gpm. Toward the east in northeastern Montana, the Eagle becomes less permeable and is not a major aquifer.

Additional hydrologic information is needed to conserve or develop the water resources, especially in the Virgelle Sandstone. This aquifer is continuous across the United States-Canadian border and effects of water use may be transmitted across the border. Potentiometric maps and aquifer testing are needed to provide information on direction and rate of ground-water movement, as well as areas of recharge and discharge. The Virgelle is extensively used in the Great Falls area where local overdrafts have been reported. The effects of overuse need to be determined and the potential for artificial re- charge or ways to increase natural recharge need to be studied.

Judith River and Kootenai aquifers

The Judith River and Kootenai aquifers occur from northwestern and central Montana. In eastern Montana they thin and become less permeable. The Judith River aquifer consists of lenticular beds of sandstone and shale and reaches a thickness of about 500 ft in the Bearpaw Mountains. The Kootenai Formation contains several important sandstone aquifers, commonly called the Cat Creek Sands. These sands are usually less than 100 ft thick, whereas the total Kootenai thickness is about 700 ft in some areas.

Ground-water hydrology of the aquifers is poorly known because not enough wells exist to allow preparation of detailed potentiometric maps. Recharge is reasoned to be from precipitation. Discharge is to wells, streams, or by evapotranspiration in areas where the water table is near the land surface. Flowing wells occur where the Kootenai is confined, as in a small area west of Lewistown (Feltis, 1973).

Wells believed to be in the Judith River yield as much as 50 gpm. Feltis (1973) reported on a well in the Kootenai that yielded 300 gpm.

Basic ground-water information is needed for the Judith River and Kootenai aquifers in order to understand the flow system, including the possibility of interaquifer leakage, and to design plans for water management.

Madison and associated Paleozoic aquifers

The Madison Group (also Madison Limestone) is an extensive limestone aquifer that occurs in nearly all of the study area. A regional description of the Madison aquifer was prepared by Swenson and others (1975). Thickness of the Madison increases toward the center of the Williston Basin in northwestern North Dakota where it is about 2,300 ft thick. The Madison is exposed near major structural uplifts. These uplifts are usually identified by mountainous landscapes. The areal extent of the Madison is only generally known because the geologic structure is complex and few drillers' logs are available. The U. S. Geological Survey is improving knowledge of the aquifer through a systematic investigation that is to be completed in September 1980.

Streamflow and precipitation recharge the Madison where it is exposed; leakage from adjacent aquifers also may recharge the aquifer. Ground-water movement is generally to the north and northeast in Montana. Discharge is to streams, springs, other aquifers, or wells. Numerous springs discharge from the Madison in Montana, and Giant Spring near Great Falls, Montana flows about 300 cubic feet per second (cfs). Wells yield from several hundred to several thousand gallons per minute. Industrial wells that withdraw water for use in oil fields have caused declines of water levels of as much as several hundred feet at places. Water temperature in the Madison increases with depth below land surface and ranges from about 50° Fahrenheit (F) to at least 250°F.

More hydrologic data are needed if supplies from the Madison aquifer are to be developed properly. Additional observation wells are required for a more accurate potentiometric map. Aquifer testing is needed to prepare maps showing the areal distribution of transmissivity and storage. Inventory and

discharge measurements of springs are necessary to provide information on natural discharge. Identification of aquifers that are hydraulically connected to the Madison and measurement of water levels in observation wells in the aquifers would provide information regarding leakage to and from the Madison aquifer. The studies by the U.S. Geological Survey should supply much of the needed data. Development of water in the Madison aquifer will be more efficient if development plans are based on the known behavior of the aquifer, as determined from field measurements and hydrologic models. The high water temperatures at depth in the Madison aquifer may indicate a potential source of thermal energy.

Natural recharge is normally minor because the high-water table, reduces space available for recharge. The use of wells to lower the water table increases space for recharge and captures water formerly occurring as surface runoff or evapotranspiration. Normally only part of the rejected recharge can be converted to recharge.

A preliminary model of the Madison aquifer in the Powder River Basin and adjacent areas was prepared by Konikow (1976). The model simulated the effect of proposed withdrawals of water from wells at the rate of 20 cfs for 100 years, for use in coal transportation. An estimated 200 cfs flow through the Madison, mostly from recharge along outcrops in the Bighorn Mountains and the Black Hills; the presence of springs in the Black Hills suggests that part of the recharge is rejected because the water table is shallow. Sources of withdrawn water in the model included salvaged rejected recharge, ground water in storage, and water otherwise lost by natural discharge. Predicted declines in water levels in the Madison ranged from about 300 ft to a maximum of about 600 ft. Declines would be less if significant leakage occurs to the Madison from other aquifers.

HYDROGEOLOGIC MAPS

Major surface exposures of valley-fill, basin-fill, Flaxville, Fox Hills and lower Hell Creek, Judith River, Eagle, Virgelle, Kootenai, and Madison, and associated Paleozoic rocks are shown on a series of 19 hydrogeologic maps that accompany this report. The maps, at a scale of 1:250,000, cover the Upper Missouri River Basin in increments of 1-degree latitude by 2-degrees longitude (fig. 1-19).

The maps were assembled by the Montana Bureau of Mines and Geology and the U. S. Geological Survey from reference material. Considerable variation in mapping detail exists within the study area. In many areas, only small-scale reconnaissance mapping was available in several small areas. No attempt to map the subsurface extent of the aquifers was made because it was beyond the scope of the study.

To assist in the ground-water resource evaluation, the hydrogeologic maps show the location, yield, and depth of hundreds of large-capacity wells that have been developed in the basin. The well data are from a search of an estimated 50,000 well records of the Montana Bureau of Mines and Geology for wells yielding 70 gpm or more. These wells represent an unknown fraction of the total number of large-capacity wells that have been drilled in the basin because mandatory reports by drillers have only been in effect for a few years.

EFFECTS OF GROUND-WATER USE

Although a large number of water-right appropriations have been issued to ground-water users in the Upper Missouri River Basin, no comprehensive system now exists for reporting the amount of water each user actually withdraws. Without a system of cataloguing either the number and yield of wells or an accurate report of metered use of ground water, no meaningful estimate of historic or present use is possible.

The U.S. Geological Survey, in cooperation with the lead water-resource agency in each of several western states, began a pilot study in 1979 to determine withdrawal water use. A comprehensive field inventory of water use is scheduled for 1980. The inventory will include use of satellite photography to monitor irrigation practices and will include metering of pumps for rate and duration of use.

In Montana, an interagency task force will be established to ascertain the roles and needs of the several federal and state agencies relative to the acquisition, storage, retrieval, and dissemination of water-use data. The U.S. Geological Survey will be the funding agency; the Montana Department of Natural Resources and Conservation will function as lead agency, carry fiscal responsibility, and will publish a resultant report.

The initial study will last five months. Its purpose is to outline a plan for designing and implementing a Montana Water Data Base which will be useful, functional, and responsive to the needs of state water-resource management agencies for policy making, planning, budgeting, and management of Montana's water resources. Further, the data base will be compatible and complimentary to the National Water-Users Data System of the U.S. Geological Survey. The Montana Department of Natural Resources and Conservation will use the water-use data system to help evolve a State Water Plan. Both surface-water and ground-water use will be determined through the proposed system.

Hydrographs of key wells

The U.S. Geological Survey in cooperation with the Montana Bureau of Mines and Geology has operated 44 observation wells in the study area with 10 or more years of record through 1975 (table 3). Hydrographs of 9 of these wells (figures 20-28) were selected to show representative trends at key locations in the valley-fill, glacial, basin-fill, Flaxville, and Virgelle aquifers. No long-term observation well records are available for Judith River, Kootenai, or Madison and associated Paleozoic aquifers.

Water-level fluctuations in a well reported to be in valley-fill deposits in northeastern Chouteau County are shown in figure 20. From 1947 through 1954 the record showed only small changes in water level. In 1955, however, a much larger range in annual changes began and has continued through 1975. In addition, the record shows a gradual residual decline in ground-water storage is occurring. This change in the water budget may be caused by pumpage of irrigation water.

Water-level fluctuations shown in figures 21-23 indicate response to natural recharge and discharge to valley-fill aquifers. No adverse effects of local pumping of wells are evident. The observation well near Bozeman (fig. 21) is located in an area having many high-capacity irrigation wells.

Figure 24 shows the hydrograph of a well that taps a highly productive valley-fill aquifer in eastern Roosevelt County. Minor residual storage changes are shown by the declining water level between 1946 and 1962. Beginning in 1963 and extending through 1975, the record shows a significant increase in ground-water storage. During the latter period the water level in the well rose about 8 ft. The increase in storage may be due to excessive application of irrigation water or leakage from irrigation ditches.

Table 3.--Observation wells in the Upper Missouri River Basin with at least 10 years of record through 1975

County	Township range, section	Well depth (feet)	Period of record	Aquifer
Beaverhead	6S, 7W, 6	107	1964-73	Basin-fill
Do	6S, 7W, 30	270	1965-74	Valley-fill
Do	6S, 8W, 18	76	1965-74	Basin-fill
Do	7S, 8W, 3	40	1965-74	Do
Do	7S, 9W, 24	25	1965-74	Valley-fill
Do	8S, 9W, 1	47	1966-75	Do
Blaine	31N, 24E, 6	70	1960-75	Do
Do	35N, 24E, 9	52	1966-75	Flaxville
Chouteau	29N, 13E, 21	210	1947-75	Valley-fill
Fergus	17N, 19E, 7	510	1966-75	Eagle
Gallatin	1N, 4E, 25	101	1951-74	Valley-fill
Do	1S, 4E, 25	50	1951-75	Do
Do	2S, 4E, 13	11	1947-75	Do
Do	2S, 5E, 22	165	1953-71	Basin-fill
Do	3S, 4E, 11	18	1963-75	Valley-fill
Garfield	14N, 30E, 11	10	1965-74	Do
Do	16N, 40E, 18	15	1965-74	Do
Do	18N, 40E, 1	158	1965-75	Fort Union
Glacier	33N, 6W, 6	89	1956-71	Two Medicine

Table 3.--Observation wells in the Upper Missouri River Basin with at least 10 years of record through 1975--continued

County	Township, range, section	Well depth (feet)	Period of record	Aquifer
Glacier	33N, 6W, 12	400	1966-75	Virgelle
Do	33N, 6W, 12	250	1966-75	Two Medicine
Do	33N, 6W, 16	18	1957-71	Glacial
Do	33N, 7W, 9	13	1956-71	Do
Hill	32N, 15E, 17	180	1961-75	Do
Jefferson	1N, 1W, 28	unknown	1965-75	Valley-fill
Judith Basin	16N, 12E, 7	10	1964-75	Do
Madison	4S, 6W, 16	56	1964-74	Basin-fill
Do	4S, 6W, 27	132	1962-74	Do
Do	5S, 6W, 14	160	1964-74	Do
Do	5S, 6W, 17	310	1962-73	Do
Do	6S, 7W, 15	109	1965-74	Do
McCone	19N, 48E, 11	52	1961-72	Valley-fill
Phillips	31N, 34E, 8	15	1947-75	Do
Richland	27N, 56E, 3	75	1963-75	Do
Roosevelt	26N, 46E, 6	15	1962-71	Do
Do	28N, 49E, 36	52	1963-75	Do
Do	28N, 57E, 28	29	1946-75	Do

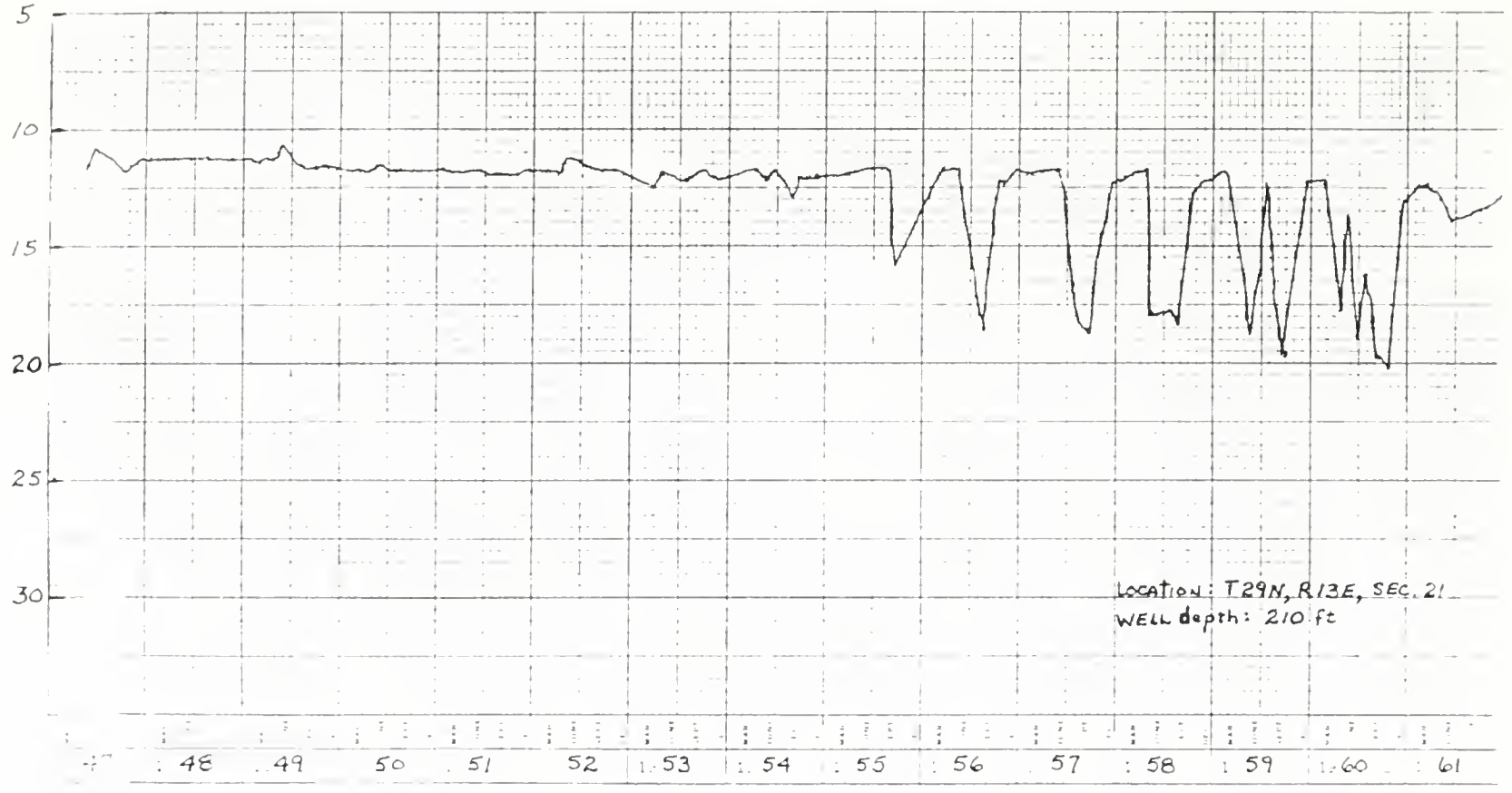
Table 3.--Observation wells in the Upper Missouri River Basin with at least 10 years of record through 1975--continued

County	Township, range section	Well depth (feet)	Period of record	Aquifer
Toole	36N, 2W, 8	17	1961-75	Glacial
Valley	26N, 45E, 8	16	1962-71	Valley-fill
Do	27N, 42E, 26	27	1966-75	Do
Do	27N, 42E, 36	30	1966-75	Do
Do	27N, 45E, 31	30	1962-75	Do
Do	27N, 45E, 34	23	1962-75	Do
Do	34N, 40E, 1	unknown	1965-75	Glacial

Upper Missouri River Basin
Level B Study

Figure 20

Hydrograph showing water-level fluctuations in a valley-fill alluvial aquifer in Chouteau County

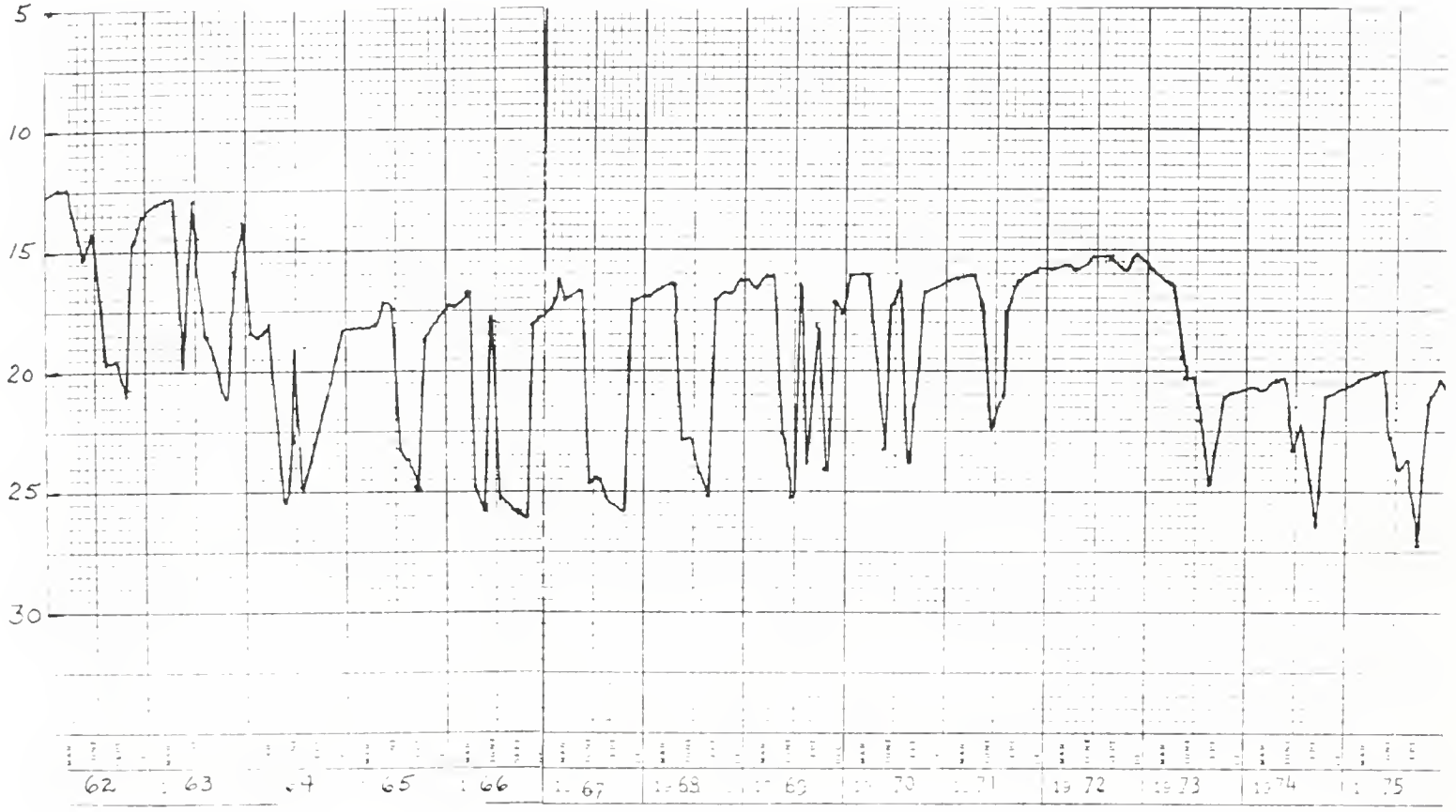


SOURCE: U.S. Geological Survey

Upper Missouri River Basin
Level B Study

Figure 20

Hydrograph showing water-level fluctuations in a valley-fill alluvial aquifer in Chouteau County--continued



SOURCE: U.S. Geological Surve

Upper Missouri River Basin
Level B Study

Figure 21

Hydrograph showing water-level fluctuations in a valley-fill alluvial aquifer in Gallatin County

SOURCE: U.S. Geological Survey

Upper Missouri River Basin
Level B Study

Figure 21

Hydrograph showing water-level fluctuations in a valley-fill alluvial aquifer in Gallatin County--continued

SOURCE: U.S. Geological Survey

Upper Missouri River Basin
Level B Study

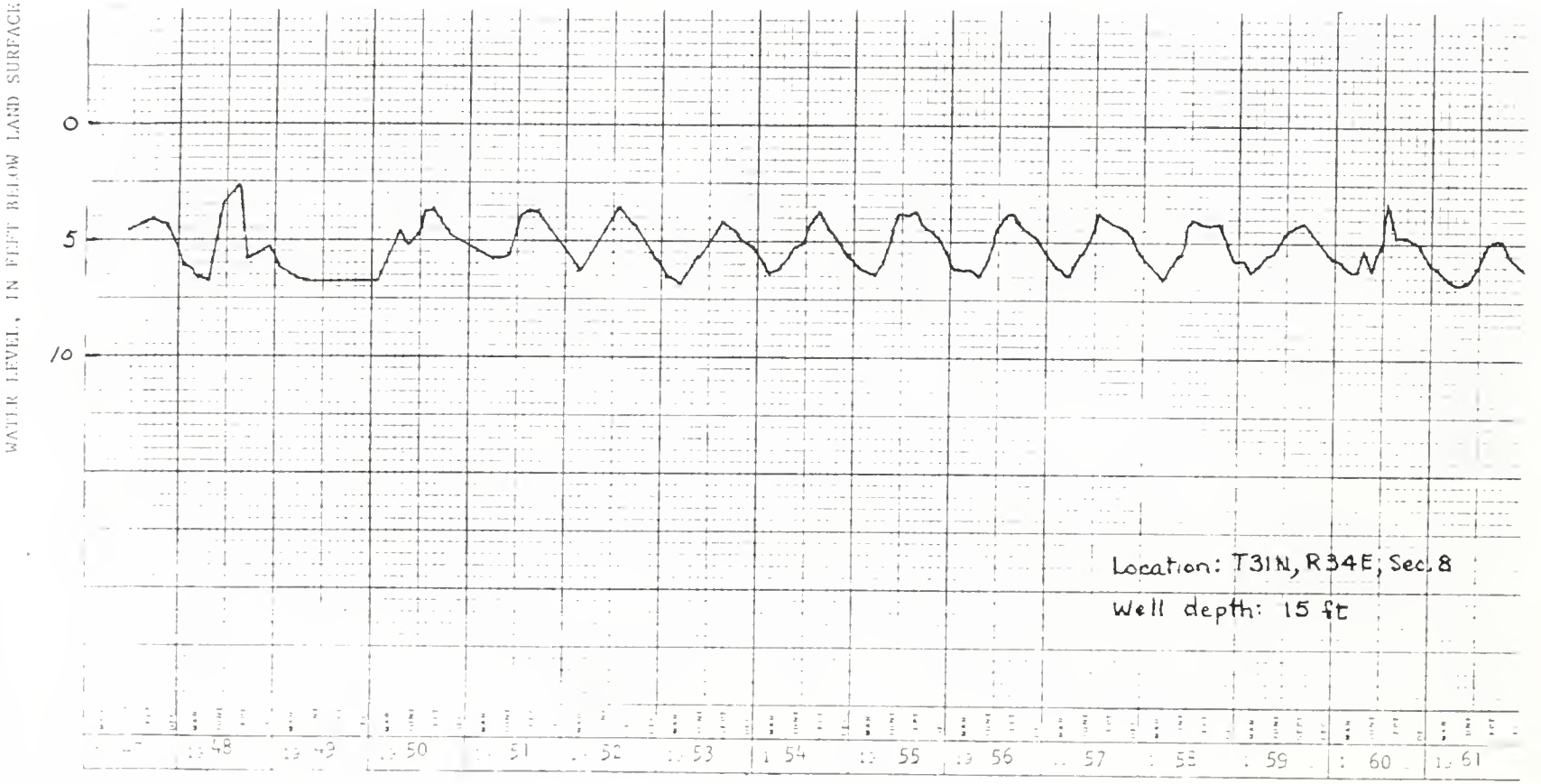
Figure 22

Hydrograph showing water-level fluctuations in a valley-fill alluvial aquifer in McCone County

Upper Missouri River Basin
Level B Study

Figure 23

Hydrograph showing water-level fluctuations in a valley-fill alluvial aquifer in Phillips County

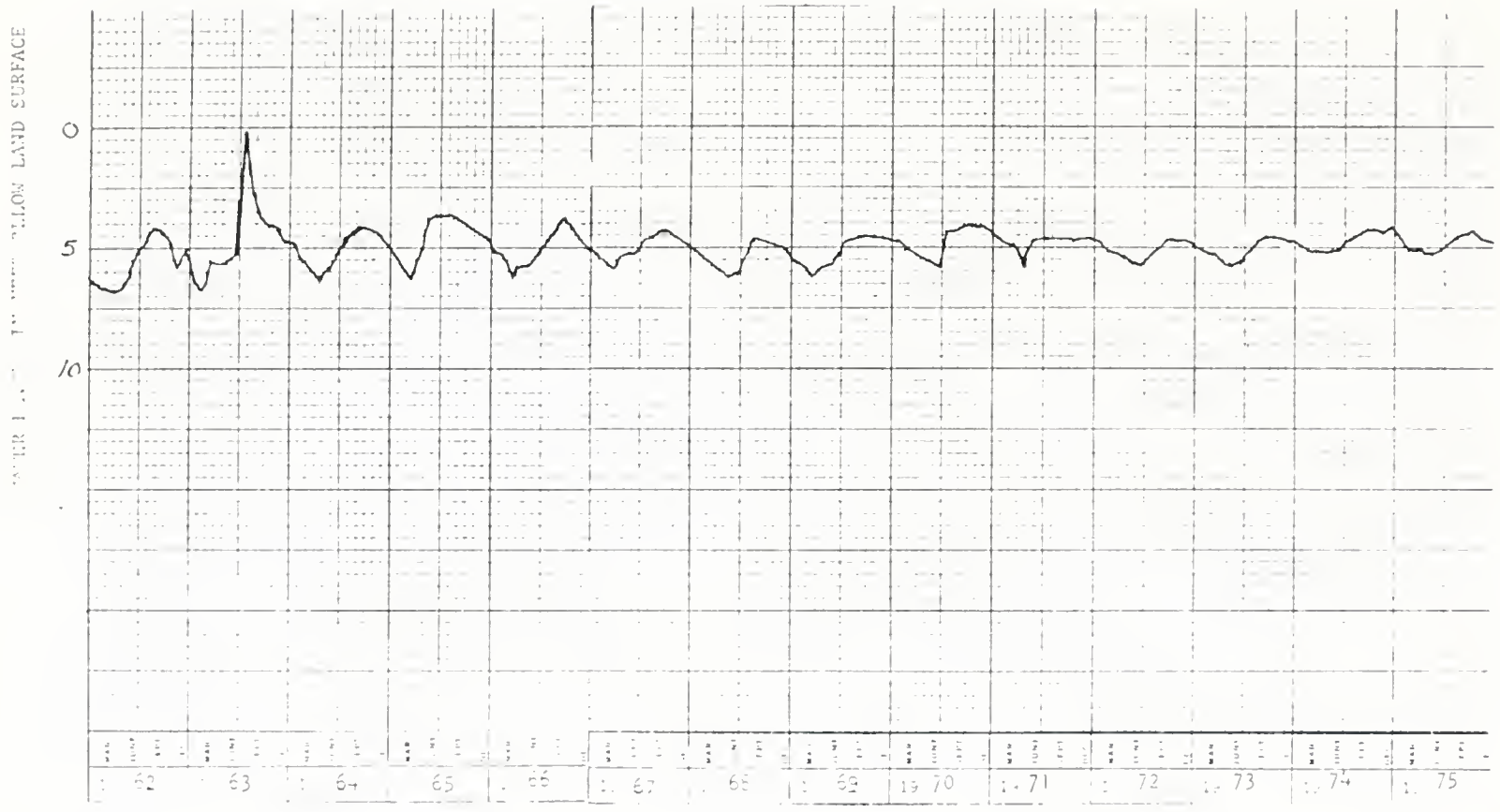


SOURCE: U.S. Geological Survey

Upper Missouri River Basin
Level B Study

Figure 23

Hydrograph showing water-level fluctuations in a valley-fill alluvial aquifer in Phillips County--continued

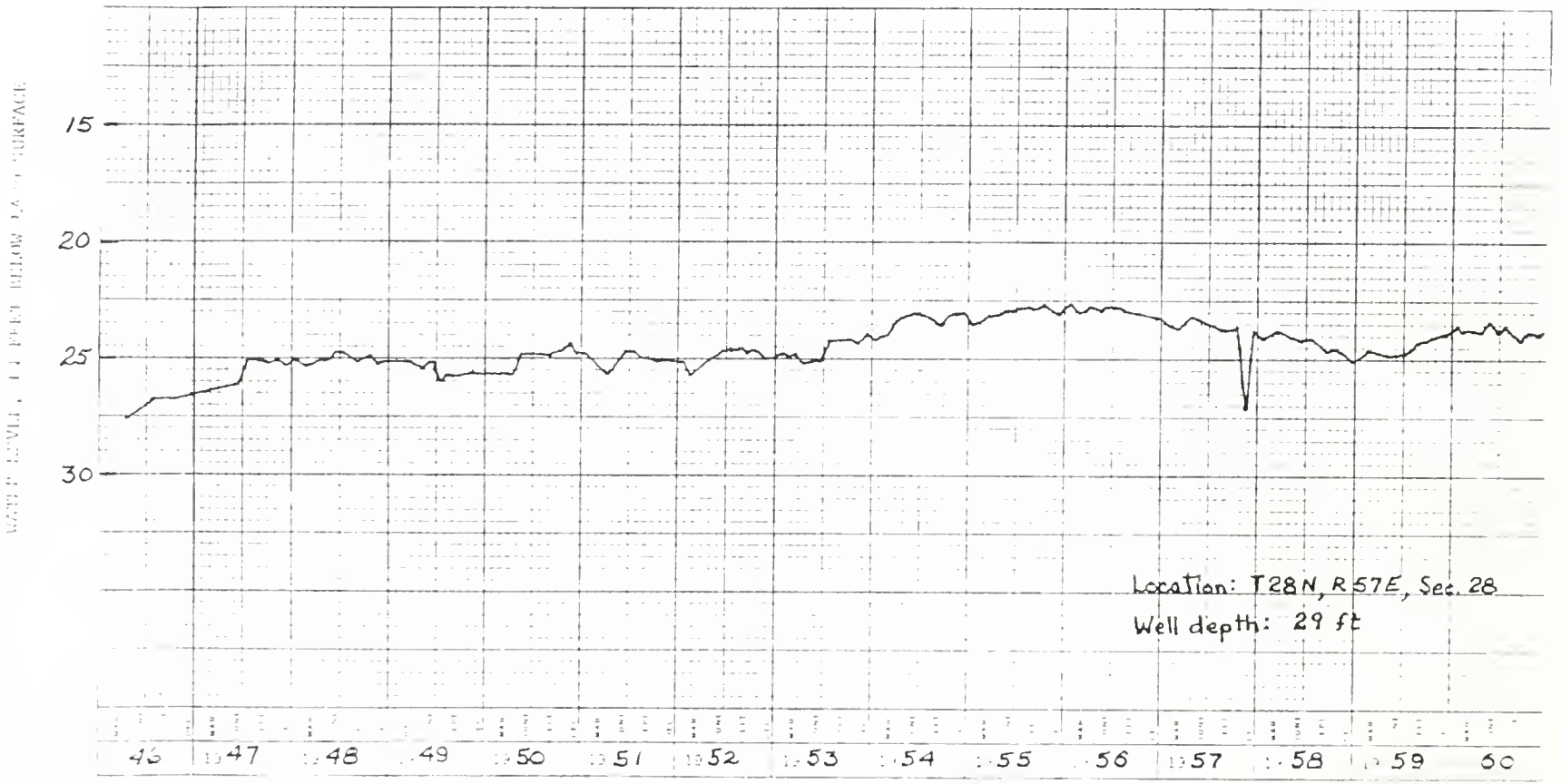


SOURCE: U.S. Geological Survey

Upper Missouri River Basin
Level B Study

Figure 24

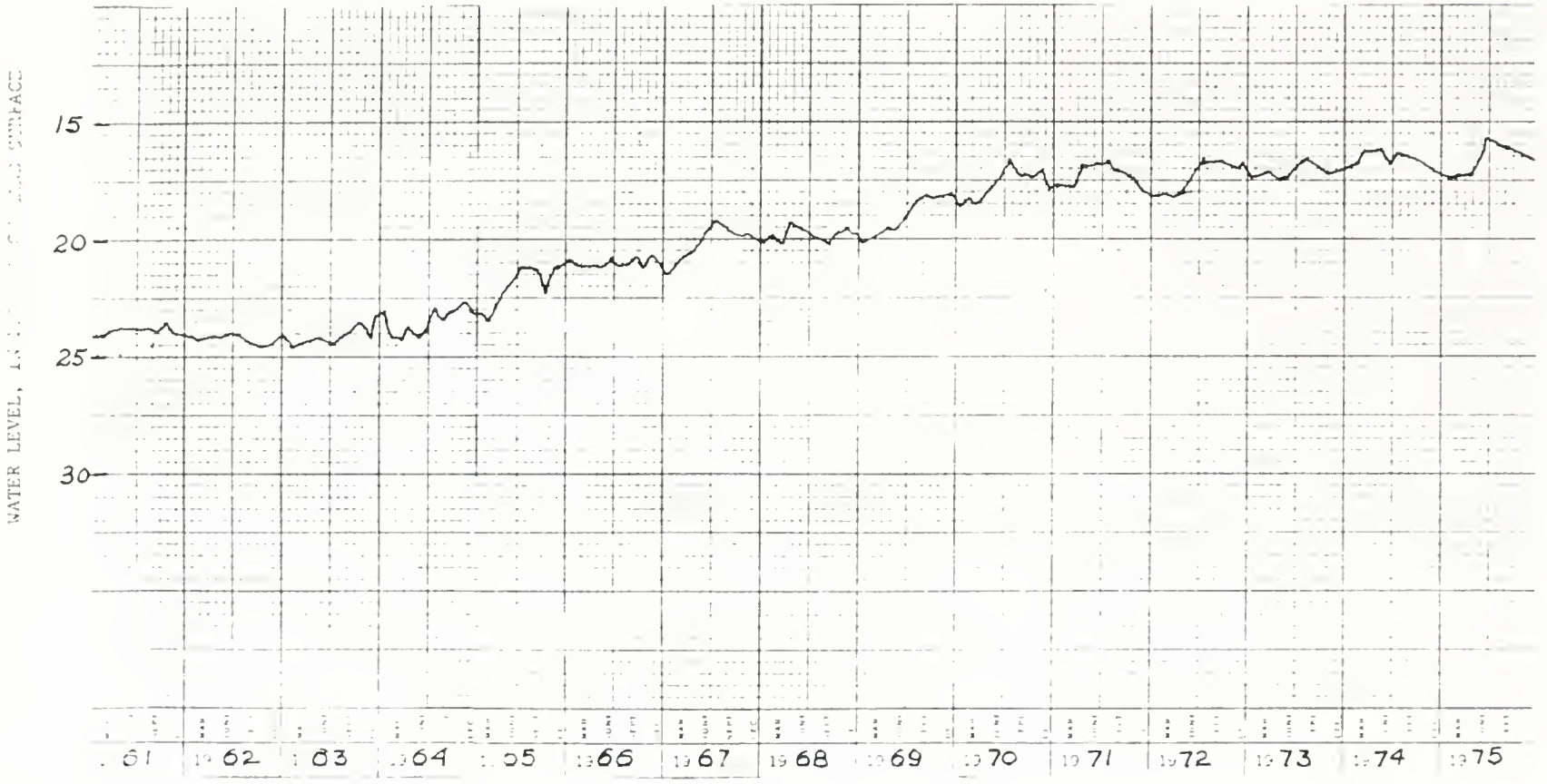
Hydrograph showing water-level fluctuations in a valley-fill alluvial aquifer in Roosevelt County



Upper Missouri River Basin
Level B Study

Figure 24

Hydrograph showing water-level fluctuations in a valley-fill alluvial aquifer in Roosevelt County--continued.

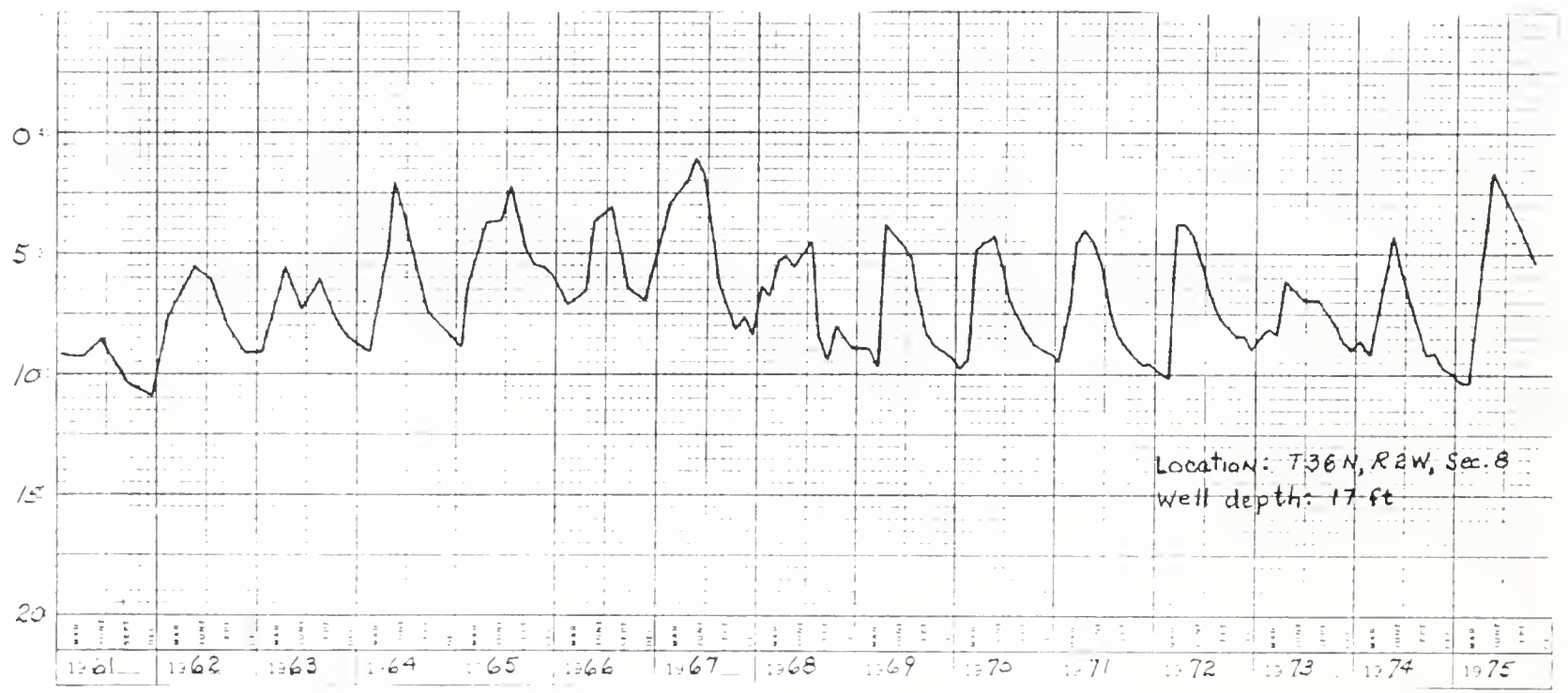


SOURCE: U.S. Geological Surve

Upper Missouri River Basin
Level B Study

Figure 25

Hydrograph showing water-level fluctuations in a glacial aquifer in Toole County

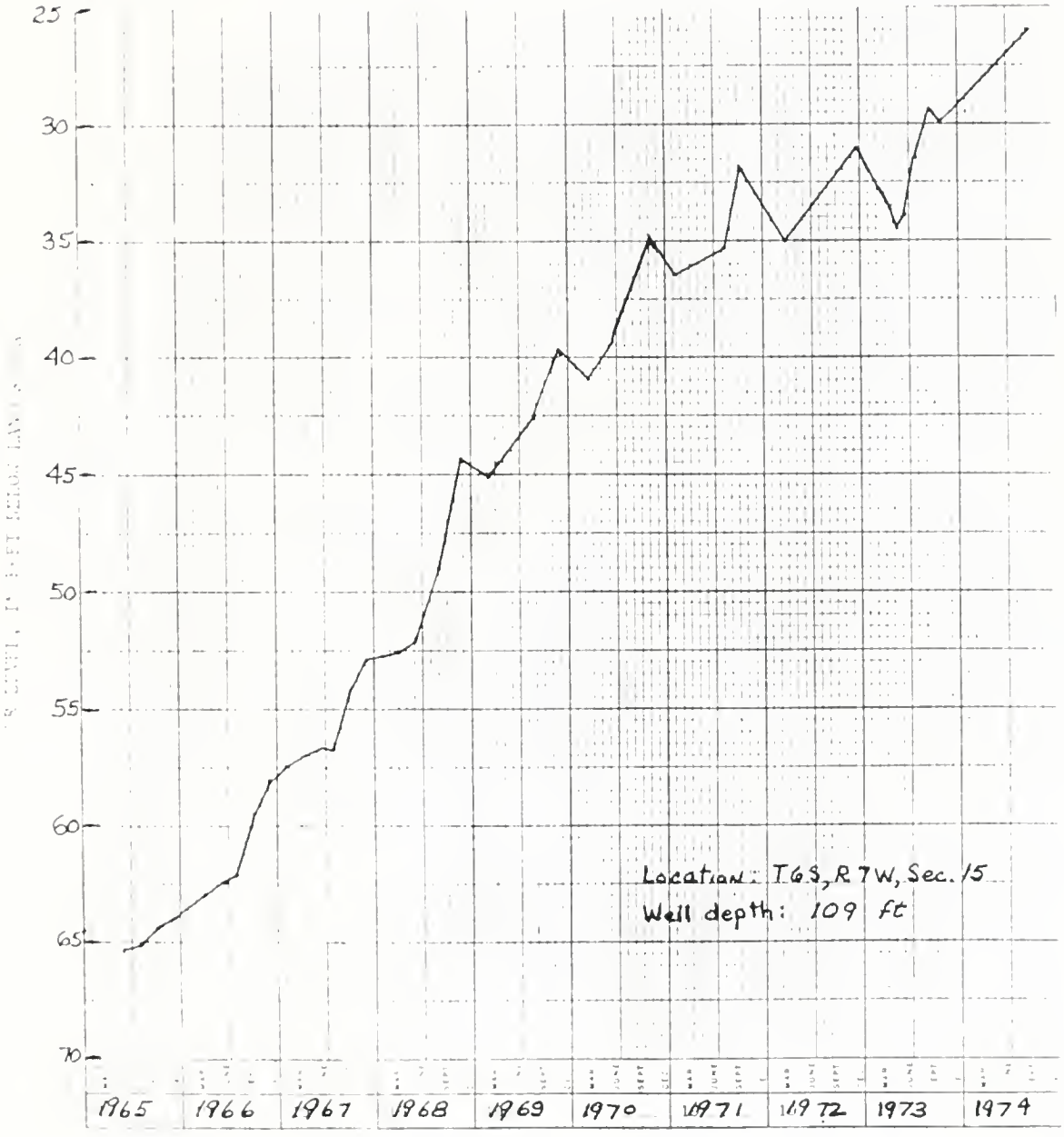


SOURCE: U.S. Geological Survey

Upper Missouri River Basin
Level B Study

Figure 26

Hydrograph showing water-level fluctuations in a basin-fill aquifer in Madison County

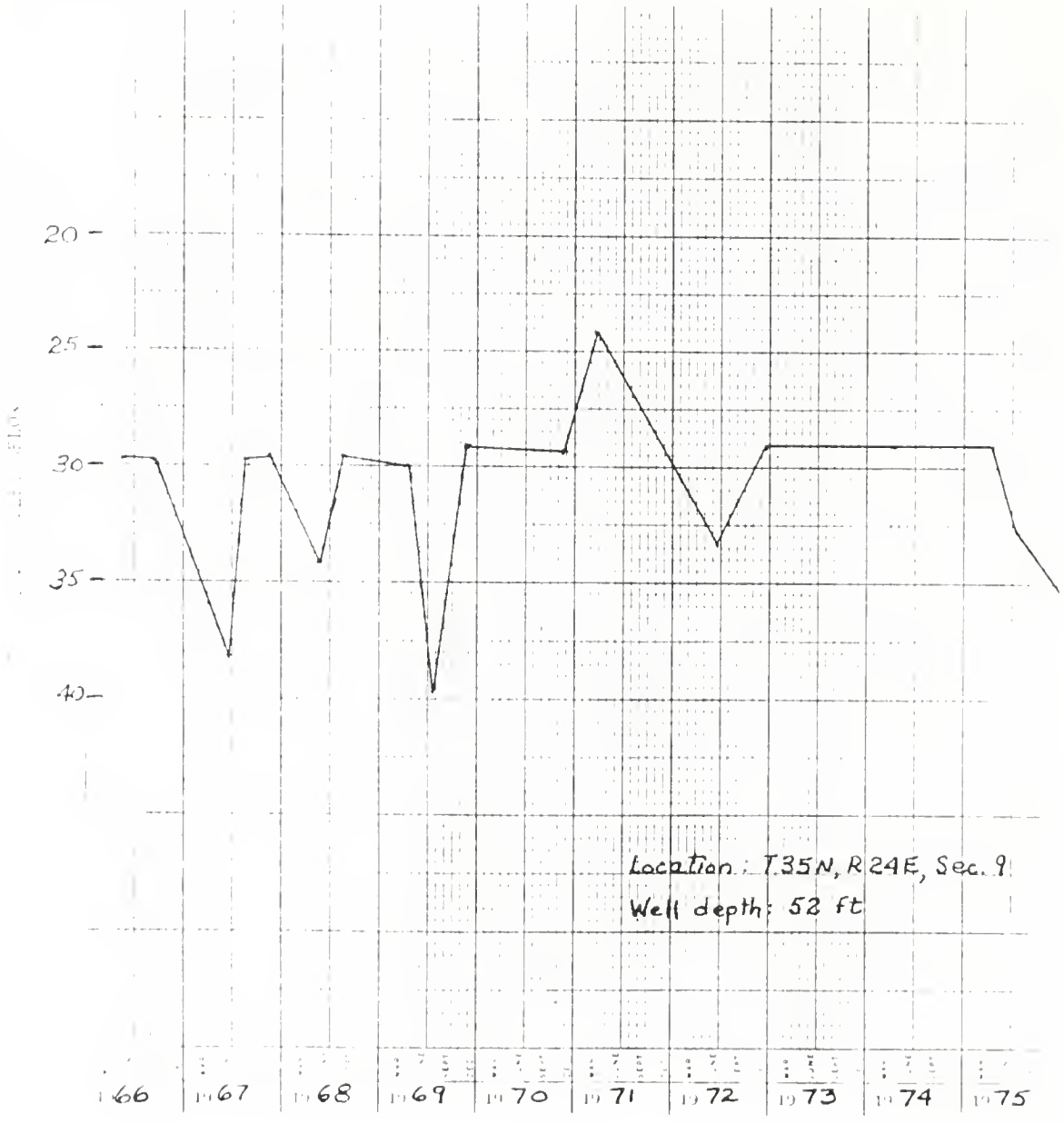


SOURCE: U.S. Geological Survey

Upper Missouri River Basin
Level B Study

Figure 27

Hydrograph showing water level fluctuations in the Flaxville aquifer in Blaine County

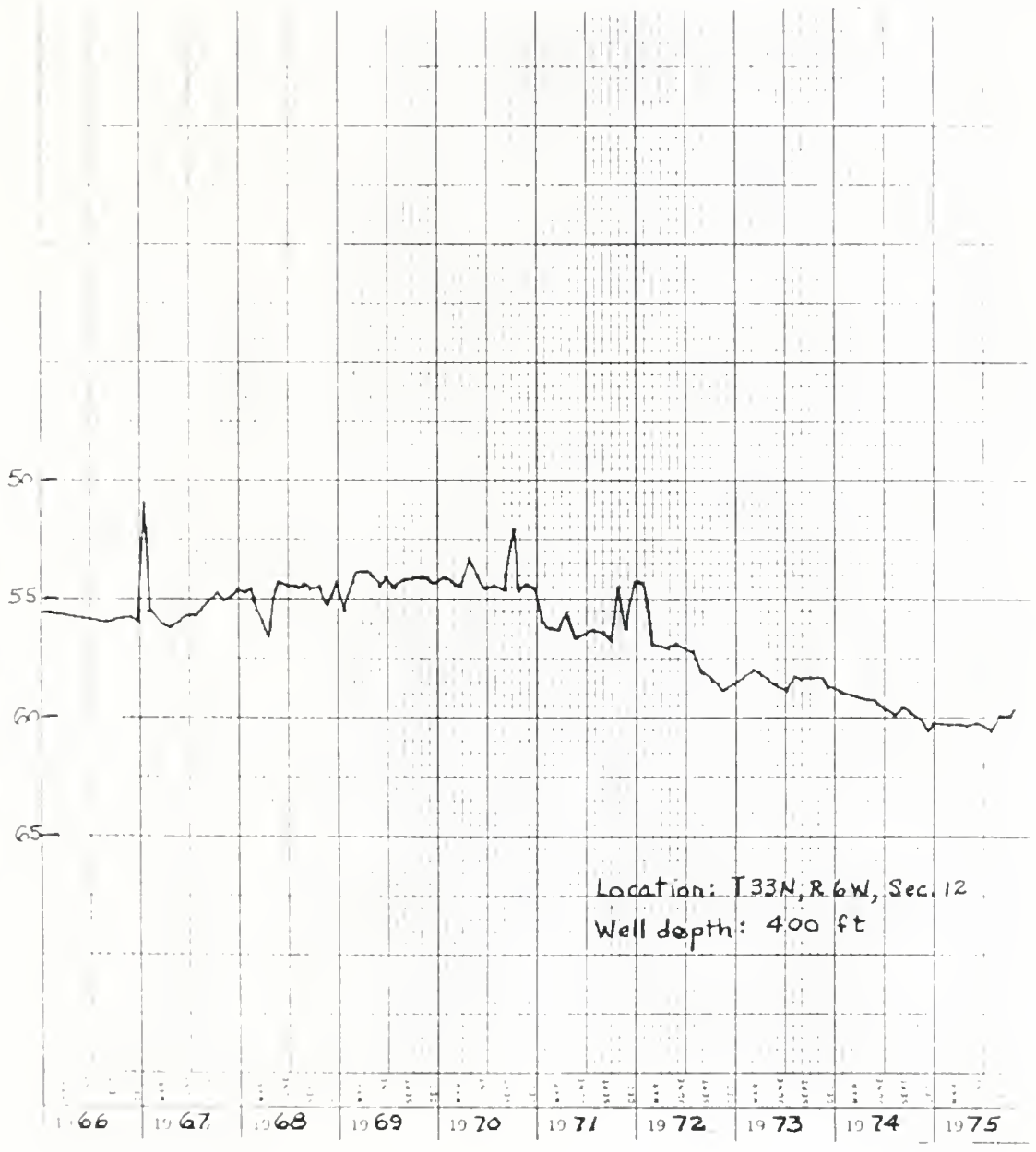


SOURCE: U.S. Geological Survey

Upper Missouri River Basin
Level B Study

Figure 28

Hydrograph showing water-level fluctuations in the Virgelle aquifer in Glacier County



SOURCE: U.S. Geological Survey

Water-level fluctuations in a glacial deposit aquifer in northwestern Toole County are shown in figure 25. The record shows cyclic responses to local recharge and discharge. No long-term ground-water storage increases or decreases are evident from the record.

Figure 26 shows a large increase in ground-water storage in a basin-fill aquifer near Dillon in Madison County. The 40-ft rise in water level from 1965 to 1974 is equalled or exceeded by other nearby observation wells. Recharge to the ground-water system is from a local irrigation project. Rapid changes in ground-water storage can cause local problems if the effects are not closely monitored.

Water-level fluctuations in the Flaxville aquifer in northern Blaine County are shown by figure 27. The large fluctuations are apparently caused by pumping of nearby high-capacity wells. The record is relatively poor but does show no residual decline of storage between 1966 and 1975. Recharge, therefore, is in balance with discharge from the aquifer at the location studied.

The Virgelle aquifer has been monitored for water-level fluctuations at Cut Bank between 1966 and 1975 (fig. 28). The record shows a gradual residual decline in water level since 1970, possibly as a result of local overpumping. The closest exposure and recharge area is several miles east of Cut Bank (fig. 5).

RECOMMENDATIONS FOR INTEGRATING GROUND WATER IN BASIN PLANNING

Although several water-management plans have been implemented in the Upper Missouri River Basin, numerous alternative plans for improvement in water supply may be designed. Management plans can be derived from information on all available sources of water supply, expected demands for current and future types of water use, constraints on desired use, and the effects of implemented use. Development of a ground water supply or incorporation of ground water into basinwide management of water resources requires various types of hydrologic information and procedures. A typical sequence of events is described below, although administrative, hydrologic or legal constraints may dictate different sequences.

COLLECTION AND INTERPRETATION OF HYDROLOGIC DATA

Hydrologic data and interpretations provide hydrogeologic understanding and predictive capability to aid the design of water-management plans that can lead to improved water use. The information and data needed for such planning consists of:

1. Knowledge of location and type of lateral and vertical aquifer boundaries. This information is needed to define the geometry of the flow systems. Types of boundaries include: a stream or lake that is hydraulically connected to an aquifer, confining rock that completely or partially confines flow in an aquifer, or an areal change in aquifer properties. Boundaries are identified by data collection and interpretation. For example, boundaries of aquifers can be determined from geologic mapping, well logs, or the observed response of the aquifer to pumping or to other hydraulic stresses. If a stream forms a boundary of an aquifer, the water interchange influences the stream. The contact between unconfined and confined zones

of an aquifer also represents a type of boundary. The unconfined zone of an aquifer is subject to the draining of and filling with ground water; the confined zone is subject to pressure changes. A relatively large amount of ground water per unit volume of aquifer may be released from or taken into storage in the unconfined zone, compared to the amount that may be released from or taken into storage by pressure changes in the confined zone.

2. Inventory of existing wells and test holes, and aquifer testing. Inventory and testing can provide information on the geologic and hydraulic properties of the flow systems, and on changes in ground water storage with time. For example, logs of wells and test holes may be useful to determine the depth to the contacts between aquifers and confining beds. Water levels in observation wells may be used to prepare water table or potentiometric maps that indicate direction of ground water movement. Water level changes measured in observation wells are useful to calculate changes in ground water storage. Aquifer tests determine the hydraulic properties of the aquifers, such as the transmissivity and specific yield or storage coefficient. Data describing the hydraulic properties are necessary for calculations designed to predict the behavior of the aquifers in response to water use.

Response of the aquifers to use may be determined using data describing the geologic and hydraulic properties of the aquifers. A simple problem may be solved with a few calculations by a skillful hydrologist. A complex problem may require a simulation model in order to incorporate and integrate all data, including aquifer properties, necessary for an accurate solution. Various types of analog or mathematical simulation models are used routinely to help understand and predict behavior of aquifers under hypothetical conditions.

3. Preparation of water budget. After this basic information is

obtained, a water budget for the aquifers can be prepared from general data. Water budgets serve to indicate average recharge, changes in storage, and discharge; and they help to emphasize relative magnitudes of water sources, water uses, and water losses. Budgets may also provide information on the general long-term behavior of the aquifers and contribute to an understanding that may lead to better use of the aquifers.

DESIGN OF WATER MANAGEMENT PLANS

A simple development plan may involve artificial recharge, withdrawals from wells, or ground water mining. A comprehensive plan might include the use of ground water based on information on snowpack, surface runoff and storage, stream-aquifer interrelations, water quality, and expected fluctuations in water supply and demand. Design of water management plans offers the challenge of integrating information on the known behavior of hydrologic systems with goals designed to improve water use.

Most water management plans are designed with the goals of alleviating shortages in water supply and reducing the harmful effects of saline water. Most plans involve a redistribution of water supplies in time and location in order to improve availability. The ground water reservoir can contribute toward these goals in many ways. Water management plans that utilize the ground water reservoir are listed below to indicate the variety possible.

1. Withdrawal from wells in selected locations to control sources of water depleted with time.
2. Recharge to aquifers in selected locations to control movement and storage of water with time.
3. Reuse of available water supply through schemes that successively capture the part of the water supply that is not consumed with each use.

4. Use of valley-fill aquifers in tributary valleys as off-channel reservoirs by recharging surplus streamflow in the tributaries to the aquifers.

5. Salvage of water normally evapotranspired by plants, using discharging wells to lower the water table.

6. Reduction of saline discharge water from aquifers by planting crops that reduce recharge to the aquifers, or by wells and surface drains that control movement of the saline water.

7. Plugging of flowing wells in confined aquifers to conserve ground water and to reduce the lowering of water levels.

8. Use of an aquifer, that underlies two adjacent surface-drainage areas, as a reservoir common to both areas by means of storage, withdrawal, and transfer techniques.

9. Mining of ground water to obtain a temporary water supply, even though the ground water may not be replenished for a long time.

10. Withdrawal from wells in an aquifer in a multiaquifer system so that the aquifer boundaries and interaquifer leakage help to sustain the withdrawal rate.

11. Use of wells to lower a high water table in a recharge area of an aquifer, in order to increase the rate of recharge.

TESTING OF WATER MANAGEMENT PLANS

Normally, a plan is not implemented until tested in the field. Testing does not indicate lack of confidence in hydrologic data or analyses, only a desire to insure that the selected plan is sound, as evidenced by verification. Field testing of a selected water management plan may proceed by trial in the area of analysis for a limited time period. For example, withdrawals from industrial wells in the Fox Hills Sandstone in the Cedar Creek

anticline area of eastern Montana were planned for 1964-84 and began on schedule in 1964. A hydrologic analysis was made and the magnitude of declines in water levels were predicted (Taylor, 1965). However, periodic measurements of water levels in observation wells were made in order to compare predicted and observed declines before State agencies permitted the continuation of scheduled withdrawals. Alternatively, a plan may be tried over part of the area for a limited time period. Field-measurement procedures must be designed and data collected carefully to insure that collected data are sensitive to the expected results of the plan. Data of the required accuracy must be obtainable with currently available field instruments and methods of procedure. Field verification of the expected response of the hydrologic system may prove the value of the selected plan. However, the decision to implement a water management plan also requires economic justification, expressed as a proven net benefit from the plan (Howe, 1971). Net benefit is the sum of all benefits from the plan, less the sum of all costs of the plan, including any damages caused by the plan.

IMPLEMENTATION OF WATER MANAGEMENT PLANS

The final step for incorporation of ground water into basin-wide management of water resources is full implementation of a selected plan. However, the plan must conform to State or interstate regulations for water administration. Other possible constraints include availability of required capital, and cooperation among participants. After implementation of a selected plan, a field monitoring program should be maintained to determine if the plan is producing the expected response in the hydrologic system and contributing benefits to the water users and managers.

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Key to Hydrogeologic map Symbols

Figures 1-19

Qal	Quaternary alluvium
Qg	Quaternary gravel
QTg	Quaternary-Tertiary gravel
QTt	Quaternary-Tertiary terrace deposit
Tg	Tertiary gravel
Tf	Tertiary Flaxville Gravel
Kfh	Cretaceous Fox Hills Sandstone. Includes lower Hell Creek sandstone member where present
Kjr	Cretaceous Judith River Formation
Ke	Cretaceous Eagle Sandstone
Kv	Cretaceous Virgelle Sandstone
Kev	Cretaceous Eagle and Virgelle, undifferentiated
Kk	Cretaceous Kootenai Formation
Ku	Cretaceous undifferentiated
Pz	Paleozoic undifferentiated. Includes Madison Limestone in most areas
● $\frac{100}{50}$	Location of high-capacity well. Upper number is reported yield in gallons per minute. Lower number is well depth in feet